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MULTISTAGE VARIABLE PROBABILITY FOREST VOLUME INVENTORY

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MULTISTAGE VARIABLE PROBABILITY FOREST VOLUME INVENTORY

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INTRODUCTION

The overall objective of the research work reported on in this document was to develop a forest volume inventory scheme which would:

(1) Be based on the use of computer processed Landsat satellite acquired multispectral scanner (MSS) data, and

(2) Produce results in a short time period for a large area.

Such research work was conducted by the National Aeronautics and Space Administration's Earth Resources Laboratory (NASA/ERL), in cooperation with the Department of Natural Resources of the Navajo Nation (DNR).

Output from the inventory scheme, once developed and implemented, would be an estimate of the standing net saw timber volume (Scribner Log Rule) of a major timber species on a selected forested area of the Navajo Nation. Such an estimate would be based on the values of parameters currently used for scaled sawlog conversion to mill output (e.g. minimum log length, trim allowance, etc.)

Exact location of the study area, as well as the selection of the timber type of interest, was determined by the Manager, Branch of Forest Management, DNR, who also supplied manpower and equipment subsequently required for ground data collection.

The Application Phase of this research project was conducted in the three month period of March-June, 1978. MSS data from Landsat scene E2476-17092 (May 1976 acquisition) and aerial photography taken in April 1977 were used to locate ground plots from which data was collected in May 1978.

BACKGROUND

The Navajo Nation includes within its boundaries approximately 15 million acres of land (Figure 1). Of the total land area, 439,402 acres (or 2.93 percent) are considered commercial forest (1968 estimate), predominately ponderosa pine (Pinus ponderosa Laws). Mixed stands of Douglas fir (Pseudotsuga menziesii Mirb.), Engelmann spruce (Picea engelmanii Parry) and corkbark fir (Abies lasiocarpa var. arizonica (Merrian) Lennon) occur in the higher elevations intermixed with small clumps of Aspen (Populus tremuloides Michx.)(USDI, 1970).

The commercial forest land is subdivided into the Defiance Unit and the Chuska-Lukachukai Unit (Figure 2). These two units are separated by open lands, non-commercial forests (predominately pinyon pine (Pinus edulis Engelm.)) and by an arm of the Canyon de Chelly National Park.

The Defiance Unit, consisting mainly of residual timber and previously cut over land (USDI, 1970) was chosen for this research work. This unit contains 192,026 acres of commercial forest land which is approximately 44 percent of the total forest area. Timber

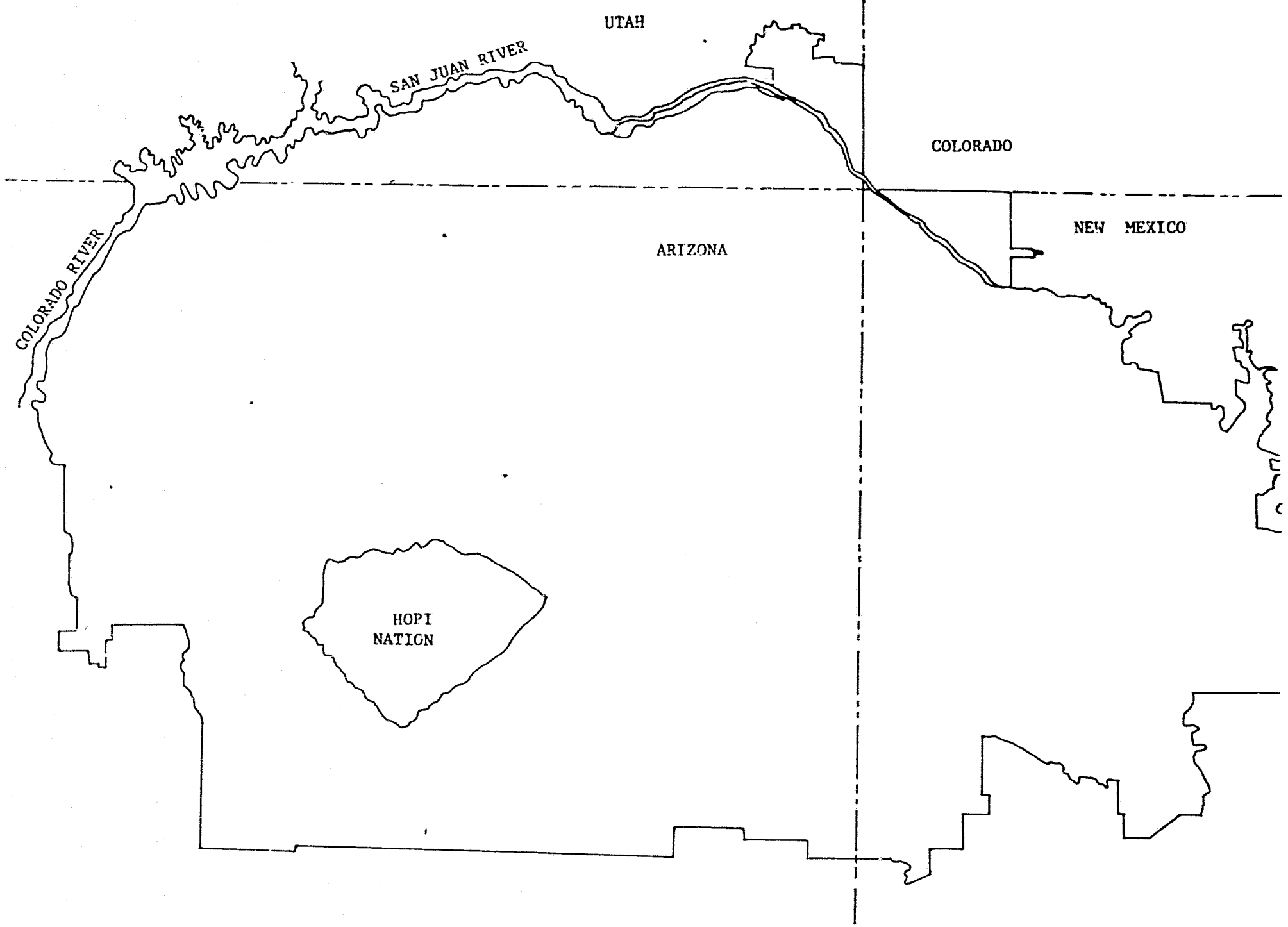

Figure 1. NAVAJO NATION

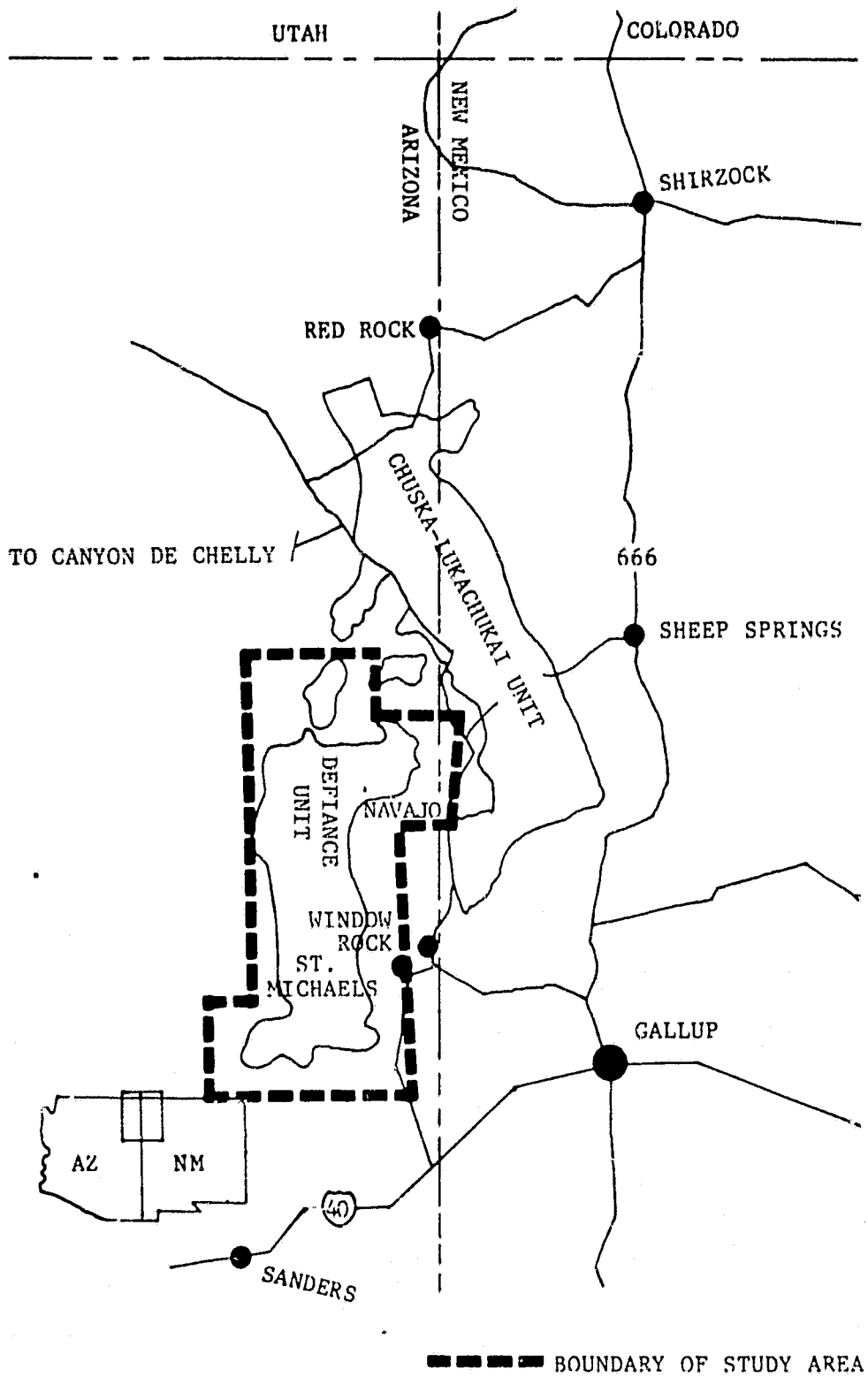

Figure 2. FORESTED LANDS OF THE NAVAJO NATION, AND LOCATION OF THE STUDY AREA.

on this unit is predominately ponderosa pine, with 93 percent of the unit classified as medium in site index (50-74 ft. at a base age of 100 years)(USDI, 1970). The remaining seven percent is listed as poor (site indicies of less than 50). The last inventory, with an effective date of July 1968, estimated a composite net mean of 3165 board feet/acre (Scribner rule) for the ponderosa pine on the Defiance Unit (USDI, 1970), with a projected ingrowth (net) of 56 board feet/acre (Scribner rule).

TECHNICAL APPROACH

At the initiation of this research work, it was recognized that numerous sampling designs could be utilized to estimate timber volume. At the same time however, two major constraints were present which severely limited the selection of the sampling framework which would subsequently be applied in this research work. It therefore became necessary to examine sampling techniques in light of these constraints, and choose one which met the need of the research work, while at the same time permitting the inventory to be conducted within the limits of the contraints in effect.

The first constraint placed on the inventory design was associated with the resources available to complete the necessary work. As was stated earlier, the study area contained 192,026 acres of commercial forest lands. A one percent survey, based on the use of 1 acre ground plots, would thus result in the selection of 1,921 sample plots, each of which would require

visitation, measurement, and analysis of the data collected. Such a number of sample plots would consume too much time and manpower.

The second constraint which influenced the selection of an inventory scheme was the requirement that the use of Landsat acquired Multispectral Scanner (MSS) data be integrated into the scheme developed. In the final outcome, this constraint has the same effect as the first, since the smallest unit capable of being sampled from the original Landsat MSS data is approximately 1.1 acres in size.

After examining several sampling/inventory design schemes, an inventory was implemented through the use of a procedure known as Multistage Variable Probability Sampling with replacement (MVPS). This technique, demonstrated by Langley (1975) and Aldrich (1970) as a sound method of obtaining estimates, is based on the integration of multistage inventory design and variable probability sampling with replacement. (Sampling with replacement simply means that after each sample selection is made, the sample unit selected is replaced into the population and hence has another chance to be selected in a subsequent sample selection.)

Variable probability sampling (VPS) with replacement (known also as probability proportional to size (PPS) or probability proportional to prediction (3P) sampling) was introduced into the United States in 1949. It was used at that time in studies

dealing with census statistics (Hanson & Herwitz, 1949). In 1958, Grosenbaugh demonstrated that cruising timber using a Bitterlich point sample with a prism or wedge gauge was VPS sampling with individual tree probabilities of selection proportional to the basal area of the tree in question. Since that time, VPS has received much more attention as an acceptable tool for sampling large populations.

In order to understand the merits of using VPS in a survey, it will be compared to sampling with equal probabilities (EPS), a technique known to most everyone dealing with sampling methods. In EPS, an estimate of the parameter of interest can be expressed as

$$Z_{EPS} = \frac{N}{n}\left(\sum_{i=1}^{n} Z_i\right)$$

where Z_{EPS} = estimate of the parameter of interest

N = number of sample units in the population

n = number of sample units selected from the population for subsequent use in estimations

Z_i = value of the parameter of interest as measured on the ith sample unit

The probability that any one sample unit is selected in EPS (with replacement) can be expressed as 1/N. As can be seen, this probability (call it P) is equal for all sample units in the population, i.e. its value does not vary for different

sample units. Knowing this, the previous equation can be rewritten as

$$Z_{EPS} = \frac{1}{n} \sum_{i=1}^{n} \frac{Z_i}{1/N}$$

$$= \frac{1}{n} \sum_{i=1}^{n} \frac{Z_i}{P}$$

The quantity Z_i/P in the equation is an estimate of the population parameter, Z, based on the measurements made at each sample unit; thus, the probability of selection for a sample unit is used as an expansion factor in essence, and results measurements made on sample units to be used to estimate the population parameters. These estimates are simply summed, and divided by the number of sample units (n) to arrive at the desired estimate.

In VPS sampling, the situation is much the same, with the exception that the probability for selection for a sample unit can be expressed as

$$P_i = e_i \Big/ \sum_{i=1}^{n} e_i$$

where: P_i = probability of selecting the ith unit

e_i = an estimate of the value of some feature associated with the parameter of interest

n = number of sample units selected from the population for use in making an estimate

As opposed to EPS in which the probability of selection for each sample unit was constant over all possible sample units, VPS employs variable probabilities of selection, based on the relative value or measurement of a feature for a particular sample unit, with respect to the sum of the values for the same feature for all sample units.

Therefore, the VPS estimation of the population parameter can be written

$$Z_{VPS} = \frac{1}{n} \sum_{i=1}^{n} \frac{Z_i}{e_i / \Sigma e_i}$$

$$= \frac{1}{n} \sum_{i=1}^{n} \frac{Z_i}{P_i}$$

where the terms are as defined earlier.

It is not only important to know the value of the estimate obtained from a sample, but it is, in addition, equally important to have an idea of the amount of variance contained in the estimate. For EPS (with replacement) the formula for the actual variance (over all samples) of the estimate is as follows:

$$\text{Variance } (Z_{EPS}) = \frac{\sum_{i=1}^{n} \left(Z_i - \bar{Z} \right)^2}{n-1}$$

$$= \frac{1}{n-1} \sum_{i=1}^{n} \left(Z_i - \frac{Z}{N} \right)^2$$

$$= \frac{1}{n-1} \sum_{i=1}^{n} \frac{1}{N^2} \left(\frac{Z_i}{1/N} - Z \right)^2$$

$$= \frac{1}{n-1} \sum_{i=1}^{n} P^2 \left(\frac{Z_i}{P} - Z \right)^2$$

in which Z is the true value of the population parameter of interest,

$$Z = \sum_{i=1}^{N} Z_i$$

The corresponding VPS variance can be written as

$$\text{Variance } (Z_{VPS}) = \frac{1}{n-1} \sum_{i=1}^{n} \left(\frac{Z_i}{P_i} - Z \right)^2$$

Notice that in the case of the EPS estimator, the value of the variance is determined to a large degree by the extent to which the individual sample estimates are different (vary) from the population (true) value (Z) while at the same time remaining insensitive to the constant probability of selection (1/n or P) With VPS; however, the variance term is defined by the differences between the true (population) value of Z and the ratios Z_i/P_i for each sample unit. Recall that the ratio Z_i/P_i (or Z_j/P in EPS) is an estimate of the true (population) value of Z, derived from the ith sample unit. With EPS sampling the ratio (Z_i/P) varies considerably, owing to the constant probability of selection. The situation is quite different however in VPS,

where the ratio Z_i/P_i is effective both by the sample measurements (Z_i) and the variable probability of selection (P_i). If the computation of the probability of selection of the ith sample unit is based on a parameter which exhibits a highly positive correlation with the parameter of interest (and which may be much more easily measured) then the ratios Z_i/P_i remain fairly constant over all samples; and, in fact, better estimate the population parameter Z. Knowing this, it is easy to see that the difference between Z_i/P_i and Z for any sample would be small, and hence the variance of the estimator (overall samples) would be reduced when compared to EPS.

The EPS variance estimate is an unbiased estimator of the population variance. It is quite simple to demonstrate that the VPS variance estimate is also unbiased (only if the sample units have actually been selected with probabilities equal to the individual sample unit P_i). This can be accomplished by calculating the expected value of the estimator over all samples of size n:

$$E\ (\text{Variance VPS}) = E\left(\sum_{i=1}^{n}\left(\frac{\frac{Z_i}{P_i} - Z}{n-1}\right)^2\right)$$

$$= \frac{1}{n-1}\left(\sum_{i-1}^{n} \frac{Z_i}{P_i}\right)$$

$$= \sum_{i=1}^{N} P_i\ (Z_i/P_i$$

$$= \sum_{i=1}^{N} Z_i$$

$$= Z$$

In order to examine the relative gain associated with the use of VPS, it is necessary to compare the variance of the VPS estimate to that of EPS.

Murthy (1967) developed the following equation relating the variance of the EPS estimator to that of the VPS estimator

$$\text{Variance (EPS)} = \frac{1}{n^2}\left(\sum_{i=1}^{n} \frac{Z_i^2}{P_i} - n\hat{Z}_{VPS}^2\right) + \frac{1}{n} \text{ Variance (VPS)}$$

Simply substituting the estimate of variance (VPS) for the last term, subtracting it from both sides, and simplifying, we obtain the relative gain associated with VPS as

$$\Delta_{VPS} = \frac{1}{n^2} \sum_{i=1}^{n} \frac{Z_i^2}{P_i}\left(N - \frac{1}{P_i}\right)$$

It is immediately apparent that as the sample size (n) increases, the gain decreases rapidly. Thus, for small sample sizes, VPS may in fact result in a better estimator than simple EPS.

Knowledge of this fact is quite important, for you will recall that one constraint on the inventory dealt with limited

resources available for conducting the necessary work. VPS will permit the use of a relatively small sample without the increase in variance that might be associated with EPS at small sample sizes.

Recall that Landsat MSS data is to be included as an integral part of the inventory design. IF VPS techniques are to be applied to the MSS data using each 1.1 acre cell as a sample unit, a "measurable" feature, correlated to timber volume (which is the population parameter of interest) must be contained within the Landsat MSS data in order to construct the sample units selection probabilities.

Landsat data can be computer processed (Anderson, 1979) to produce a product which has at least two such "measurable" features; the forest cover types on the study area and the geographic area occupied by each forest cover type. Since the study is to deal with only one timber type (viz, Ponderosa Pine), this eliminates the use of the forest cover type feature in establishing the selection probabilities for each sample unit (as required by VPS). The remaining "measurable feature" of area is also ruled out when using individual Landsat cells as the sample units, since all sample units have the same dimension and hence the same area. This results in equal probabilities for selection, a situation that one attempts to avoid in the design.

One way in which this problem can be circumvented is to increase the size of the sample units which will, in most instances, add cells of a land cover type which is not of interest. However, if all sample units are designed in such a manner that the total sample area is identical, another area related "measurable feature" associated with timber volume becomes available for use; percent of sample unit area occupied by the timber type of interest, or put another way, density. It should be obvious that an area that is 50 percent forested would contain a proportionately larger volume of timber than an area that is only 10 percent forested, all other things being equal. And since the product produced by the computer makes no distinction between varying forest density on an individual Landsat cell basis, this "higher percent/higher volume" relationship holds true for sample units composed of numerous Landsat cells. However, the increase in sample unit size also makes collection and analysis of the ground data much more time consuming, since more trees need to be measured, more data must be analyzed, etc.

VPS is only part of the overall inventory scheme, since as mentioned earlier, the inventory would also incorporate multistage sampling concepts, the theory for which has been developed by Langley (1975) as part of his PhD dissertation. Multistage sampling is quite useful when the primary sample units are too large to facilitate total measurement of the parameter of interest on the ground, for it permits the addition of subse-

quent "stages" of sampling which selectively subdivide the primary sample units into smaller and smaller units, until, after one or more additional stages have been added, the sample unit size is such that measurements and data analysis can be made with relative ease.

An integration of VPS and multistage sampling constitutes the Multistage Variable Probability Sampling (MVPS) design selected for the inventory. Several features of MVPS serve to enhance its utility, among which are:

1. Probabilities of selection are based on features correlated with timber volume. This fact dictates that areas containing larger timber volumes stand a much higher chance of being selected, the effect of which is to concentrate inventory resources on the most productive areas.

2. The estimate produced by MVPS inventories are unbiased so long as the sample units are selected with probabilities truly proportional to the feature measured.

3. Variance values associated with the estimator retain the desirable characteristics associated with VPS estimators, such that smaller sample sizes will not have a substantial adverse effect on the outcome.

METHODOLOGY AND RESULTS

A four stage MVPS was selected for use in this study. Landsat MSS data was used as the first stage; aircraft acquired

aerial photography was employed as the second and third stages; with ground data collection encompassing the fourth stage.

The objective of this task was to produce an estimate of the net board foot volume (Scribner rule) of the standing ponderosa pine timber on the Defiance Unit, using a multistage forest volume inventory scheme, with variable sample selection probabilities. The inventory designed to accomplish this task required that both Landsat acquired MSS digital data and aircraft acquired data be used to locate one acre ground plots, which were subsequently visited by ground teams conducting detailed tree measurements using an optical dendrometer. The measurements produced by the dendrometer were then punched on computer input cards and were used as input to a computer program developed by the U.S. Forest Service (Grosenbaugh 1974). The resulting individual tree volume estimates were then expanded through the use of a statistically defined equation to produce the volume estimate for the entire area of interest.

Various questions have been addressed in order to determine optimal procedures for such a multistage design. Some of these questions were "How many aircraft stages are desirable?", (as the number of stages influences sample design), "What is the appropriate altitude for each aircraft stage?" (as altitude influences sensor resolution), and "What is the best time of the year to acquire Landsat and aircraft data for this purpose?" However, because of limited resources, it was necessary to

restrict the scope of this research to include only one aircraft mission. Subsequently, it was decided to fly the aircraft at 12,000 feet AMSL because this was near the ceiling for widely available light aircraft that do not carry oxygen supplies. The aircraft mission was flown in the spring season (May), in order to best match land cover conditions as they were when the Landsat data was collected (May 1976), to take advantage of the frequently cloud free skies, and to allow sufficient time for processing of the aerial film, photo interpretation, and sampling to take place before scheduled ground data collection.

The Defiance Unit is quite irregular in shape, as can be seen on Figure 2. In addition, boundary locations for the unit were not recorded in a form that could have been utilized in this project. Therefore, the area of interest was defined by "squaring off" around the Defiance Unit, the results of which included approximately 329,176 acres of land (See Figure 2). Those areas located outside of the Unit boundaries were composed mainly of the aforementioned open lands and pinyon pine non-commercial forests.

Before the actual multistage forest volume inventory could commence, it was necessary to convert the original four-channel Landsat digital data (NASA 1977) into single-channel geographically referenced data, containing land cover type information. Such a data conversion was accomplished through computer implemented techniques developed by NASA/ERL. The land

cover type information was geographically referenced to the Universal Transverse Mercator (UTM) map projection system (See Graham 1977 for details).

Stage 1

After Landsat digital data had been acquired, processed, and geographically referenced to the UTM map projection system, the area of interest was located (by UTM coordinates) and subsequently partitioned into the first stage sampling units, referred to as Primary Sample Units (PSU's). Each PSU was rectangular, 4.38 mile by 3.60 mile in size. Thirty-four such PSU's were required to cover the roughly 16 by 44 mile study area.

UTM corner coordinates for each PSU thus defined were used to extract the land cover information derived from Landsat data. Of particular interest was the area of each PSU (expressed in acres) occupied by ponderosa pine. This value was calculated by the computer for each PSU and output in a standard line printer tabular format.

After obtaining the acreage figures for the 34 PSU's in the area of interest, a four column table was constructed. Column one of the table simply contained a list of sequential PSU numbers; from one to 34. Column two contained the computer derived ponderosa pine acreage figures associated with each PSU. Column three contained a running summation of the acreage figures in column two. Column four contained a range value, computed from column three.

Suppose for example we are dealing with five PSU's. The table might appear as follows:

PSU	ACREAGE	Σ	RANGE	PROBABILITY OF SELECTION
1	36	36	1-36	36/135
2	25	61	37-61	25/135
3	15	76	62-76	15/135
4	43	119	77-119	43/135
5	16	135	120-135	16/135

The probability of selection for any particular sampling unit is variable and is in proportion to an estimate of the total timber volume contained in each sampling unit, as correllated with area. For this research, percent of area occupied by ponderosa pine was used as an indicator of relative timber volume, and hence was used as the sample selection delimiter. Those sample units containing higher percentages of ponderosa pine (with an assumed higher timber volume) were assigned relatively higher probabilities of selection.

The "range" statistic is based entirely on the value of the sample selection delimiter. Beginning with PSU #1 in the example, its "range" of selection is defined as being from 1 to 36, since PSU #1 contained 36 acres of ponderosa pine. Thus, the selection probability for PSU #1 is 36/135, the 135 in the denominator representing the final entry in column #3.

Similarly, the "range" for PSU #2 is 37-61 which represents a selection probability of 25/135. The same procedure is used to establish the "ranges" for the other PSU's as listed in the example.

Uniformly distributed random numbers were then generated in the interval [1, MAXΣ], where "MAXΣ" represents the final cumulative total (135 acres) in the "Σ" column of the example table (and hence the total acreage of ponderosa pine on the area of interest). These random numbers were used to select the PSU's that were considered in the next stage. This was accomplished by locating the random number in the interval [1, MAXΣ] and then determining into which PSU's "range" the random number fell. The PSU selected had a probability of selection proportional to the acreage of ponderosa pine it contained, since the probability of selection is defined as follows:

$$\frac{\text{the acreage of ponderosa pine for a PSU}}{\text{total acreage of ponderosa pine for the area of interest}}$$

The individual PSU acreages of ponderosa pine (which change for each PSU) determine the probability of selection and also were used to generate the "range" for each PSU; the range is therefore in proportion to the selection probability.

Three of the original 34 PSU's were selected for further consideration. The number three was chosen after a preliminary

analysis of the satellite data indicated that three PSU's were to be selected if a statistically desirable result was required.

Stage 2

The three PSU's selected were then located on a map, and subdivided into 100 rectangles. These secondary sample units (SSU's) were then located on color infrared positive transparencies acquired with an aircraft flying at 12,000 ft. AMSL. Forest acreage for each SSU was estimated at 97% accuracy through use of a random dot grid.

The data thus collected was analyzed for each SSU within each PSU in the manner described for Stage 1. Two SSU's were selected for each PSU chosen in Stage 1, for a total of six SSU's to be analyzed in Stage 3.

Stage 3

Each SSU was then subdivided into one acre cells and the aircraft photography was again interpreted for each ground plot (GP). Selection in this stage was based on percent crown closure of ponderosa pine. Three GP's per SSU were selected (as described under Stage 1) for subsequent ground visitation.

Stage 4

Field activities were conducted utilizing aerial photographs at various scales that contained the GP's of interest. Eighteen such GP's were visited during the week-long data collection activity.

At each GP, the four corners were located using the color IR aerial photography. Each tree on the GP was labeled, and it's height and diameter were measured and recorded. Then, using diameter as the basis for selection, a method described by Wiant (1976) was used to select sample trees.

Each sample tree was measured with an optical dendrometer. This device is a short base optical rangefinder, and produces 3 measurement values at each point measured on a tree. The first two values are used to calculate diameter of the stem at the point of measurement, and the third value is used to calculate height (or stem length) between two successive measurement locations. Measurements are made at several locations on the tree defined by: stump height, diameter at breast height (D.B.H.), and a change in product of the tree section (e.g., sawtimber, pulpwood, cull, etc.). A detailed description of the dendrometer and it's use are contained in Space, 1973. The measurement values taken were recorded on a specially designed form and were punched onto computer data cards. Bark thickness and past 10 years radial growth were measured and recorded for each tree.

Thirty-nine trees were measured with the dendrometer. Individual tree volumes were calculated from the dendrometer data on the computer input cards through the use of a U.S. Forest Service developed porgram known as "STX" (Grosenbaugh, 1974). This program permits the user to specify precise con-

straints on the manner in which the tree volumes are calculated, and thus enables users to produce tree volume estimates compatible with those produced in other inventories.

The calculated volume (in board feet) for each tree was then expanded through the use of a statistical expansion equation developed for this project. The equation is of the form:

$$V_t = \frac{1}{M} \sum_{i=1}^{M} \frac{1}{p_i \; n_i} \sum_{j=1}^{n_i} \frac{1}{p_{ij} \; t_{ij}} \sum_{k=1}^{t_{ij}} \frac{1}{p_{ijk} \; q_{ijk}} \sum_{l=1}^{q_{ijk}} \frac{v_{ijkl}}{p_{ijkl}}$$

where V_t = Calculated total timber volume on the entire study area

M = Number of PSU's

n_i = Number of SSU's in the i<u>th</u> PSU

P_i = Probability of selecting the i<u>th</u> PSU

t_{ij} = Number of GP's in the i<u>th</u> SSU of the i<u>th</u> PSU

p_{ij} = Probability of selecting the j<u>th</u> SSU from the i<u>th</u> PSU

q_{ijk} = Number of trees in the k<u>th</u> GP of the j<u>th</u> SSU of the i<u>th</u> PSU

p_{ijk} = Probability of selecting the k<u>th</u> GP of the i<u>th</u> SSU of the i<u>th</u> PSU

v_{ijkl} = Calculated volume of the l<u>th</u> tree on the k<u>th</u> GP of the j<u>th</u> SSU of the i<u>th</u> PSU

p_{ijkl} = Probability of selecting the l<u>th</u> tree of the k<u>th</u> GP of the j<u>th</u> SSU of the i<u>th</u> PSU

A detailed description of the development and use of such an equation is found in Langley (1957).

For the 329,176 acres under consideration, a total net volume (ponderosa pine only) of 5.9064798×10^8 board feet (Scribner) was estimated, with an estimated sampling error of 5.2% (computed according to Langley 1975). This volume figure leads to a calculated 3226.03 board feet/acre (Scribner), when averaged over the 183,088 acres (Landsat estimate) on which Ponderosa Pine occurs on the study area. Such a figure represents the average volume per acre of forested lands, and is consistent with the 1968 USDI inventory calculations. In 1968, the inventory resulted in an average figure of 3165 board feet/acre. The 1968 inventory also estimated a 56 board feet/acre growth for the 10 year period ending in 1978 (USDI 1970). This would lead to a projected 3221 board feet/acre average in 1978. As can be determined, this results in a 5.03 board feet/acre difference between the 1978 inventory results reported on here and the 1968 10-year projected volume per acre estimate.

CONCLUDING COMMENTS

Multistage Variable Probability Sampling appears capable of producing estimates which compare favorably with those produced using conventional techniques. In addition, the reduction in time, manpower, and overall costs lend it to numerous applications.

Computer processed Landsat MSS data contained a sufficient amount of information to permit its use as a first stage in this multistage design. Landsat data can therefore enhance the applications of techniques requiring large area inventories. In addition, the use of Landsat acquired MSS data as a resource management information tool can alleviate certain problems associated with current methods of inventory surveys.

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